UNCLASSIFIED

AD 262 356

Reproduced
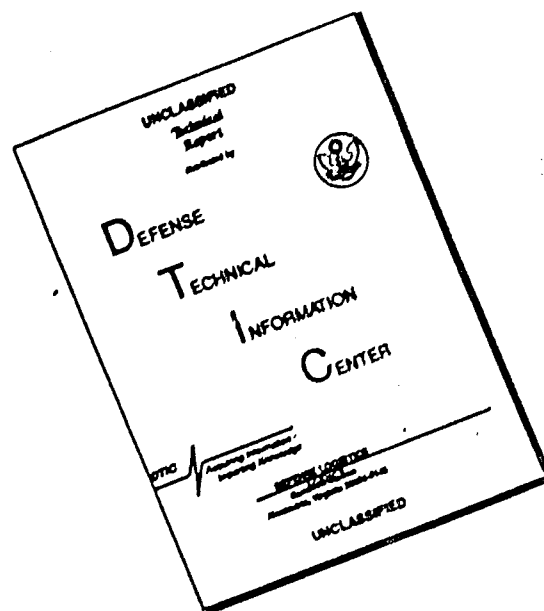*by the*

DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

OFFICE OF NAVAL RESEARCH

OFFICE OF CIVIL AND DEFENSE MOBILIZATION

by contract through

NATIONAL BUREAU OF STANDARDS

Technical Report No 1

by

William Squire

SOUTHWEST RESEARCH INSTITUTE
Department of Mechanical Sciences
8500 Culebra Road
San Antonio 6, Texas

August 1961

SOUTHWEST RESEARCH INSTITUTE
8500 Culebra Road, San Antonio 6, Texas

THE EFFECT OF REACTANT CONSUMPTION IN
NONSTEADY EXPLOSION THEORY

by

William Squire

Technical Report No. 1
Contract No. CST-362
SwRI Project No. 1-965-2

Prepared for

The National Bureau of Standards
Washington 25, D. C.

Attn: Dr. A. F. Robertson
Chief, Fire Protection Section
Building Research Division

August 1961

SOUTHWEST RESEARCH INSTITUTE
8500 Culebra Road
San Antonio 6, Texas

APPROVED:

H. Norman Abramson, Director
Department of Mechanical Sciences

SUMMARY

The effect of reactant consumption in nonsteady explosion theory is investigated by an exact numerical method and an approximate analytical treatment. Results are presented for the critical conditions and the ignition delay for supercritical conditions. The approximate analysis gives ignition delays in good agreement with the numerical solution, but the critical conditions are not obtained as accurately as in an alternative analysis due to Thomas. A comparison of temperature-time histories computed by the exact numerical method with experiments reported by Akita showed satisfactory agreement and indicated that reactant consumption was significant for wood.

LIST OF SYMBOLS

ρ -   density

c   -   specific heat

T   -   temperature

t   -   time

K   -   thermal conductivity

Q   -   heat of reaction per gram of material reacted

w   -   concentration of reactant

k   -   prefactor in Arrhenius rate expression

n   -   order of reaction

E   -   activation energy

R   -   gas constant

θ -   dimensionless temperature, $\dfrac{E}{RT_{in}^2} (T - T_{in})$

τ -   dimensionless time, $Kt/(\text{characteristic length})^2$

δ -   dimensionless reaction rate, $\dfrac{w_{in}^{n+1} \, Qke^{-E/RT_{in}}}{KRT_{in}^2}$

$$\times (\text{characteristic length})^2$$

λ -   dimensionless concentration, w/w_{in}

ς - RT_{in}/E

LIST OF SYMBOLS (Cont'd)

A - dimensionless heat transfer coefficient

B - dimensionless adiabatic temperature rise, $\dfrac{E}{RT_{in}^2} \dfrac{w_{in}Q}{\rho c}$

q - an adjustable parameter

P - a constant in Equation (14)

F( ) - a function used in the numerical solution defined in Equation (7b)

$\Delta\theta$ - step size in the numerical solution

Subscripts

in - initial

cr - critical

INTRODUCTION

The basic partial differential equations for a homogeneous combustion process with an Arrhenius type reaction rate term are

$$\rho c \frac{\partial T}{\partial t} = K\nabla^2 T - Q \frac{\partial w}{\partial t} \qquad (1a)$$

$$\frac{\partial w}{\partial t} = -kw^n e^{-E/RT} \qquad (1b)$$

The nonsteady theory is an approximate formulation which replaces the partial differential equations by ordinary differential equations giving the "average" temperature and composition as functions of time. The space variation is eliminated by replacing the Laplacian, which represents the heat conduction, by an equivalent heat loss term proportional to the difference between the "average" temperature and the ambient temperature The physical significance of the average quantities and the relation of the heat loss coefficient in the nonsteady theory to the physical boundary condition on (1) has been discussed in recent papers by Gray and Harper[1] and by Thomas[2]

In terms of dimensionless variables (defined in the List of Symbols) the ordinary differential equations are

$$\frac{d\theta}{d\tau} = \delta\lambda^n e^{\frac{\theta}{1+\epsilon\theta}} - A\theta \qquad (2a)$$

and

$$\frac{d\lambda}{d\tau} = -\frac{\delta}{B}\lambda^n e^{\frac{\theta}{1+\epsilon\theta}} \qquad (2b)$$

subject to the conditions $\theta = 0$ and $\lambda = 1$ at $\tau = 0$. The form of the

equation is independent of geometry which only enters in the determination

of the heat transfer coefficient, A.

The object of this paper is to present approximate analytical

and numerical solutions of (2) While there have been a number of

previous investigations, simplifications have been made, especially of

(2). While these approximations are justified for gaseous reactions,

which were the motivation for the earlier work, Thomas[3] has pointed out

that for solids, such as wood, where B is smaller by an order of magni-

tude, it is important to take the reactant consumption into account.

It is well known that (2) has two types of solutions depending on the

value of A/δ. For large values of A/δ, the heat generated by the reaction

can be conducted away, and there is only a small temperature rise, the

maximum value of θ being about 1. This type of solution will be referred

to as stable or subcritical. For small values of A/δ, unstable or super-

critical solutions are obtained The heat cannot be conducted away

rapidly enough, and θ approaches the adiabatic value B. The transition is

quite sharp for large values of B The important problems are:

    (1)   To determine the critical value of A/δ dividing the two
             types of solution, and

    (2)   To determine the time at which the rapid temperature
             rise begins in the supercritical case. Conventionally,

this ignition delay is defined as the time at which

$\theta = 2$. For materials such as wood with a small heat

of reaction, there is no explosion in the literal sense

but the phenomenon is similar in principle to the thermal

explosion of gases.

ANALYSIS

Both the approximate analytical solution and the numerical

solution take advantage of the absence of τ from (2). Multiplying (2b)

by $n\lambda^{n-1}$ and dividing by (2a) gives the differential equation

$$\frac{d\lambda^n}{d\theta} = -\frac{n}{B} \frac{\lambda^{2n-1} e^{\frac{\theta}{1+\epsilon\theta}}}{\lambda^n e^{\frac{\theta}{1+\epsilon\theta}} - \frac{A}{\delta}\theta} \tag{3}$$

subject to $\lambda = 1$ at $\theta = 0$. After solving this equation either analytically

or numerically, the solution can be expressed as a function of τ by the

auxiliary relation

$$\delta\tau = \int_0^\theta \frac{d\theta}{\lambda^n e^{\frac{\theta}{1+\epsilon\theta}} - \frac{A}{\delta}\theta} \tag{4}$$

The use of θ as the independent variable involves some problems as both

λ and τ are double valued functions of θ; however, these are not significant

in the specific problems under consideration, and it was found easier to

work with (3) than with the alternate form

$$\frac{d\theta}{d\lambda} = -B\left[1 - \frac{A}{\delta} \frac{\theta}{\lambda^n} e^{-\frac{\theta}{1+\epsilon\theta}} \right] \tag{5}$$

Numerical Solution

In this section, only a first order equation $(n = 1)$ is considered, and ϵ is neglected. With these simplifications, (3) can be written as an integral equation

$$\lambda = 1 - B^{-1} \int_0^\theta \frac{\lambda d\theta}{\lambda - \frac{A}{\delta} \theta e^{-\theta}} \tag{6}$$

This integral form is only valid while θ <u>increases</u> to its maximum value. However, no difficulty results from this limitation. In subcritical cases, an imaginary value of λ is obtained when the calculation is carried past the maximum value of θ. In the supercritical cases, the calculation is only carried out to $\theta = 2$ which is well below the maximum value.

The numerical solution is based on the relations

$$2\lambda(\theta) = \frac{\frac{A}{\delta} \theta e^{-\theta} + F(\theta - \Delta\theta) \cdot \frac{\Delta\theta}{2B}}{\left[\left(\frac{A}{\delta} \theta e^{-\theta} + F(\theta - \Delta\theta) - \frac{\Delta\theta}{2B}\right)^2 - 4\frac{A}{\delta} \theta e^{-\theta} F(\theta - \Delta\theta)\right]^{1/2}} \tag{7a}$$

where

$$F(\theta - \Delta\theta) = \lambda(\theta - \Delta\theta) - \frac{\Delta\theta}{2B} \frac{\lambda(\theta - \Delta\theta)}{\lambda(\theta - \Delta\theta) - \frac{A}{\delta}(\theta - \Delta\theta)e^{-(\theta - \Delta\theta)}} \tag{7b}$$

This procedure is equivalent to the well-known modified Euler method[4] of solving an ordinary differential equation. The iterative process was eliminated by the assumption $n = 1$ which made the nonlinear algebraic relation a quadratic which was solved to give an explicit formula for $\lambda(\theta)$ in terms of $\lambda(\theta - \Delta\theta)$ and θ. The method is also applicable with ϵ taken into account. The simplifying assumption was made because ϵ is in fact small and the approximate analytical solutions, with which the numerical solution will be compared, neglect ϵ.

It can be seen that the numerical solution of the basic equations only solves the first problem determining the critical value of A/δ for a given value of B, indirectly. The critical value of A/δ for a given value of B can be bounded as closely as desired by means of numerical solutions, but no explicit formula for the critical curve can be obtained. It is, therefore, desirable to consider approximate analytical solutions.

Approximate Analytical Solution

The approximate analytical solution of (6) is based on the method of successive approximations. If an approximate expression for $\lambda(\theta)$ is put into the integral on the right-hand side of (6), an improved approximation is obtained by evaluating the integral. The first approximation will be taken as

$$\lambda = 1 - \frac{q}{B}\theta \tag{8}$$

where q is a parameter to be determined by matching the first and second approximations at a reasonable value of θ. Using the initial slope gives q = 1, but the higher value obtained by a matching procedure appears desirable.

It should also be noted that within the accuracy of the approximation

$$\lambda^n \cong 1 - \frac{nq}{B}$$ (9)

Therefore, the approximate analysis can be extended to an nth order reaction by replacing B by B/n except when B is small.

Examination shows that with λ given by (8), or even with $\lambda = 1$, the integral in (6) cannot be evaluated in closed form. For $\lambda = 1$ (no reactant consumption) Gray and Harper[1] used the approximation

$$e^\theta = 1 + .72\theta + \theta^2$$ (10)

This does no allow integration in closed form when (8) is used, therefore, an analogous approximation

$$e^\theta \cong \frac{1 + .718\theta}{1 - .368\theta}$$ (11)*

---

*The constants $.718 \cong e - 2$ and $.368 \cong 1/e$ were selected to give the correct result for $B \to \infty$

was introduced in order to obtain an integrable form. Fig. 1, which compares the two approximations within the range $0 \leqslant \theta \leqslant 2$ shows that they are of comparable accuracy.

With these approximations, the relations

$$\lambda = 1 - B^{-1} \int_0^\theta \frac{1 + \left(.718 - \frac{q}{B} \right) \theta - .718 \frac{q}{B} \theta^2}{1 - \left(\frac{A}{\delta} + \frac{q}{B} - .718 \right) \theta + \left(.368 \frac{A}{\delta} - .718 \frac{q}{B} \right) \theta^2} \, d\theta \tag{12a}$$

and

$$\delta\tau = \int_0^\theta \frac{1 - .368\theta}{1 - \left(\frac{A}{\delta} + \frac{q}{B} - .718 \right) \theta + \left(.368 \frac{A}{\delta} - .718 \frac{q}{B} \right) \theta^2} \, d\theta \tag{12b}$$

are obtained. These integrals can be evaluated in closed form by well-known methods, though the resulting expressions are rather long.

The Critical Case

The critical case corresponds to the denominator in (12), being a perfect square. Algebraic manipulations gives the relation

$$\left(\frac{A}{\delta} \right)_{cr} = \left(1.454 - \frac{q}{B} \right) + \sqrt{ \left(1.454 - \frac{q}{B} \right)^2 - \left(.718 \frac{q}{B} \right)^2 } \tag{13}$$
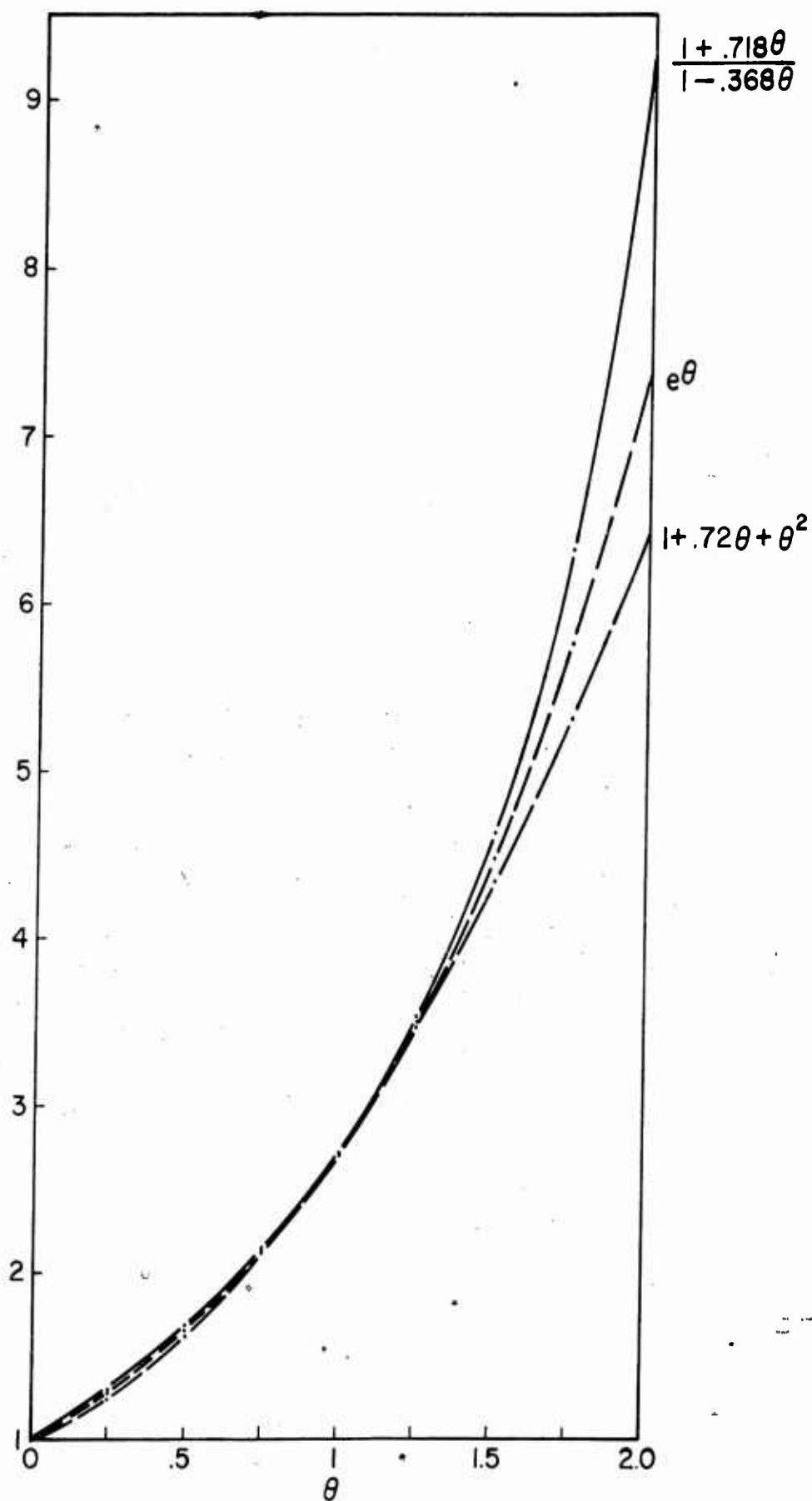
$$\frac{1+.718\theta}{1-.368\theta}$$

e^{θ}

$1+.72\theta+\theta^2$

FIGURE I. COMPARISON OF APPROXIMATIONS TO e^{θ}

for the critical value of A/δ. However, the expression does not give a definite result until q is evaluated. Introducing (13) for A/δ into (12a) gives

$$
\lambda = \int_0^{P\theta} \frac{1 + P^{-1}\left(.718 - \frac{q}{B}\right)(P\theta) - .718 P^{-2}\frac{q}{B}(P\theta)^2}{(1 - P\theta)^2} \, d(P\theta) \tag{14}
$$

where

$$
P = \sqrt{.368\left(\frac{A}{\delta}\right)_{cr} - .718\frac{q}{B}}
$$

Physically, P^{-1} represents the maximum value of θ in the critical case. Therefore, using a constant value of $P\theta$ as the matching point appears plausible. Fig. 2 shows the variation of q with B for several choices of values of $P\theta$ at which (8) and (14) match. It can be seen that q is constant until B becomes relatively small. A discussion of the resulting critical curve will be given below.

Supercritical Case

In the supercritical case, the value of A/δ is arbitrary, provided it is below the critical value. The problem is to compute the value of $\delta\tau$ for $\theta = 2$ by evaluation of (12b). It is reasonable to evaluate q by
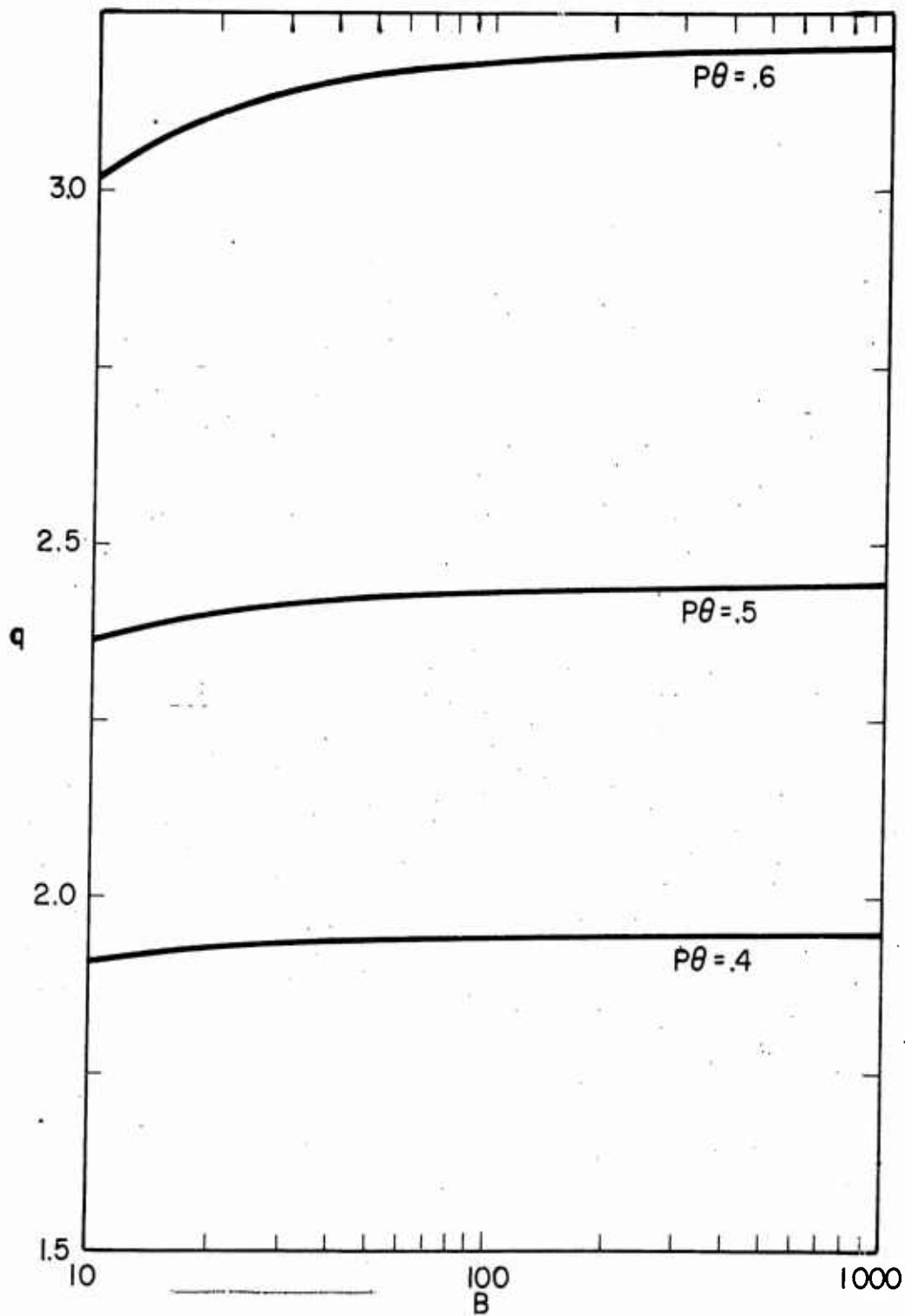
FIGURE 2. CRITICAL CASE; q OBTAINED BY
MATCHING AT DIFFERENT VALUES OF Pθ

matching at $\theta = 1$, the midpoint. The resulting values of q for several values of A/δ are shown in Fig. 3 which plots q versus B/q. It should be noted that the curves end abruptly. Corresponding to (13), the relation

$$\frac{q}{B} = \sqrt{4.344 \frac{A}{\delta} - \left(\frac{A}{\delta} + .718\right)} \tag{15}$$

can be obtained, and for a given A/δ there are no supercritical points for values of B/q smaller than those implied by (15).
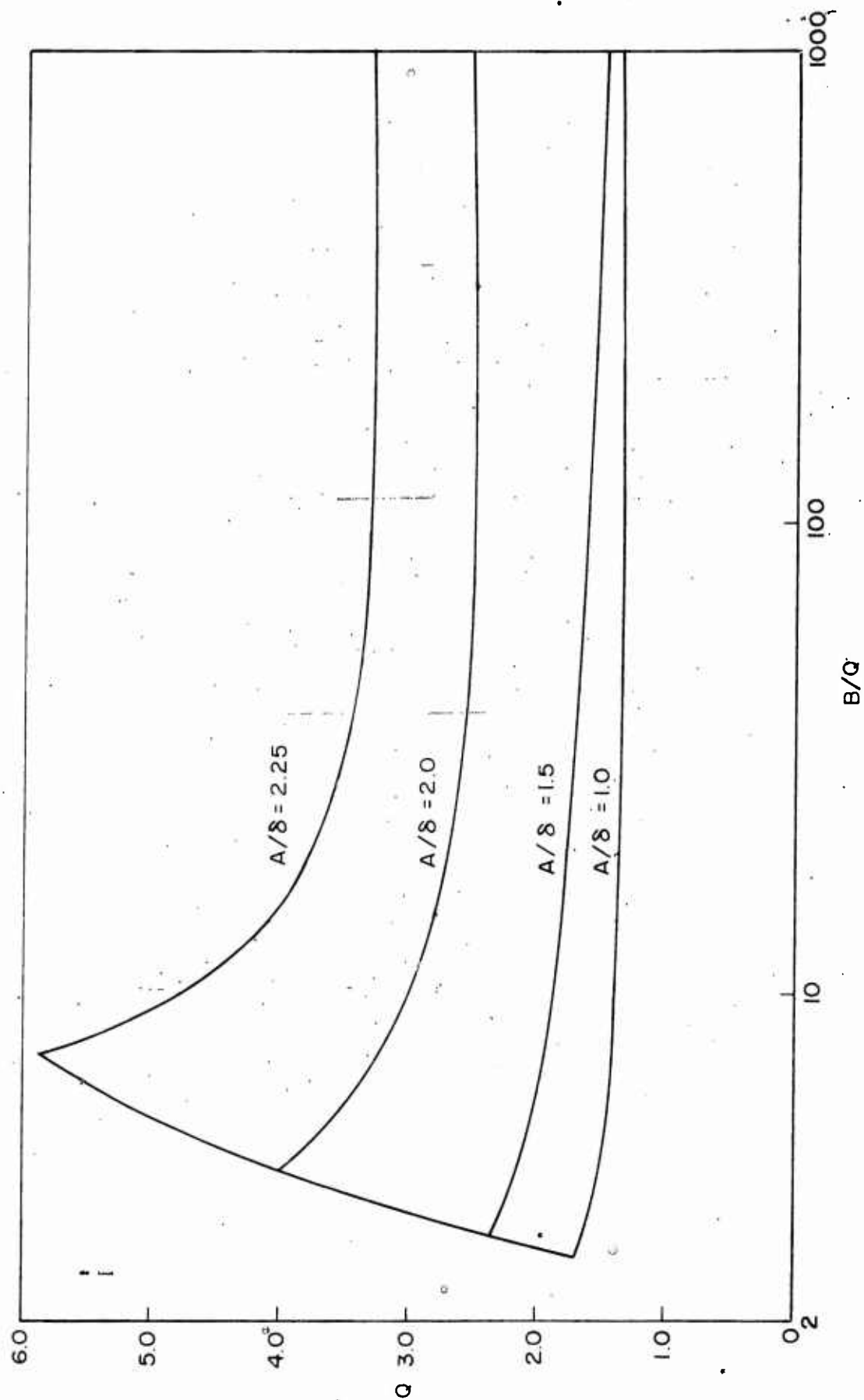
FIGURE 3. VALUE OF Q FOR VARIOUS A/δ OBTAINED BY MATCHING AT θ = 1 (SUPERCRITICAL CASES)

SPECIFIC RESULTS

The integral equation (6) was solved numerically for a number of sets of A/δ and B using $\Delta\theta = 0.1$. Some check calculations with smaller values of $\Delta\theta$ (0.05 and 0.01) indicated that the step size was sufficiently small. The results of these numerical calculations will be compared with the approximate analytical calculations of the critical conditions and ignition delay obtained in the previous section and those reported by Thomas[3]. Also, a comparison with experimental temperature histories obtained by Akita[5] will be presented.

Critical Conditions

Fig. 4 compares the value of $\frac{\delta_{cr}(B)}{\delta_{cr}(\infty)} = e \div \left(\frac{A}{\delta}\right)_{cr}$ obtained from (13), the value of q being obtained by matching at $P\theta = 0.5$, with Thomas' expression[3]

$$\frac{\delta_{cr}(B)}{\delta_{cr}(\infty)} = 1 + 2.85B^{-2/3} \tag{16a}$$

and with Frank-Kamenetskii's expression[6]

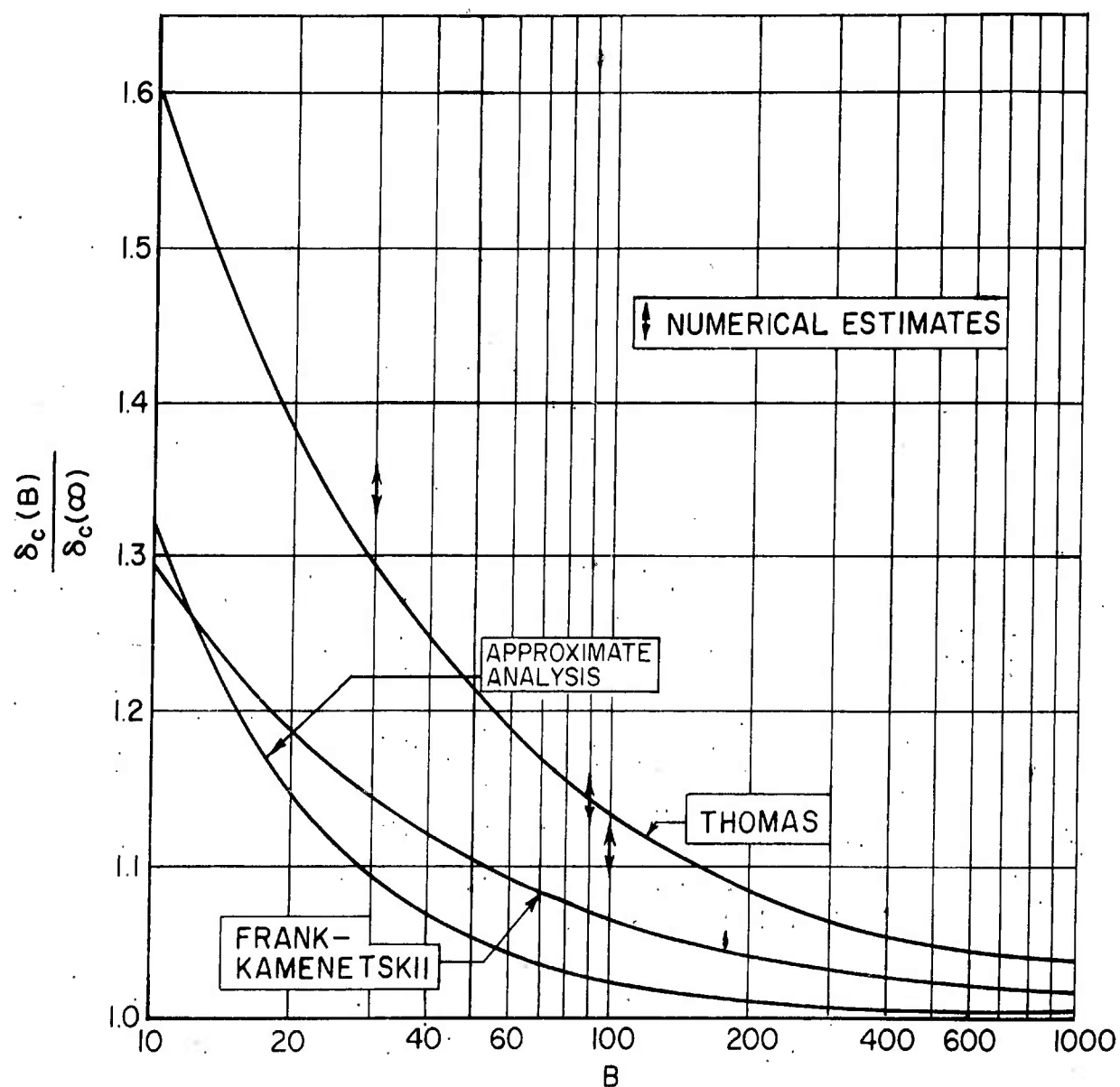$$\frac{\delta_{cr}(B)}{\delta_{cr}(\infty)} = 1 + 2.85B^{-2/3} \tag{16b}$$

FIGURE 4. EFFECT OF REACTANT CONSUMATION ON CRITICAL CONDITIONS FOR A THERMAL EXPLOSION

The limits of the stability curve found by the numerical calculations for particular values of B are indicated by $\downarrow$. While the limits were not determined closely except for B = 176, it is clear that Thomas' result is definitely superior to the others except for large B when the effect of reactant consumption is small.

Ignition Delay

The ignition delay τ_{ig} is defined somewhat arbitrarily as the time required for θ to reach 2. Fig. 5 shows $\delta\tau_{ig}$ as a function of A/δ for B = 29.4 and B = 176 as obtained by·

(1) Numerical solution of (6) combined with numerical evaluation of (4)

(2) The approximate analysis based on (12b) with q determined by matching at $\theta = 1$

(3) Thomas' approximate analysis, and

·(4) Numerical integrations carried out by Rice, Allen and Campbell[7] in which, however, reactant consumption is not taken into account rigorously.

It can be seen that in this case our approximate analysis is in good agreement with our numerical calculations .The approximate analysis of Thomas and the numerical calculations of Rice, Allen and Campbell are somewhat further off, but in the opposite direction, than our approximate treatment.

Comparison with Experimental Temperature Histories

Kinbara and Akita[4] have reported two temperature histories for sawdust spheres (contained in wire gauze) and compared the data with
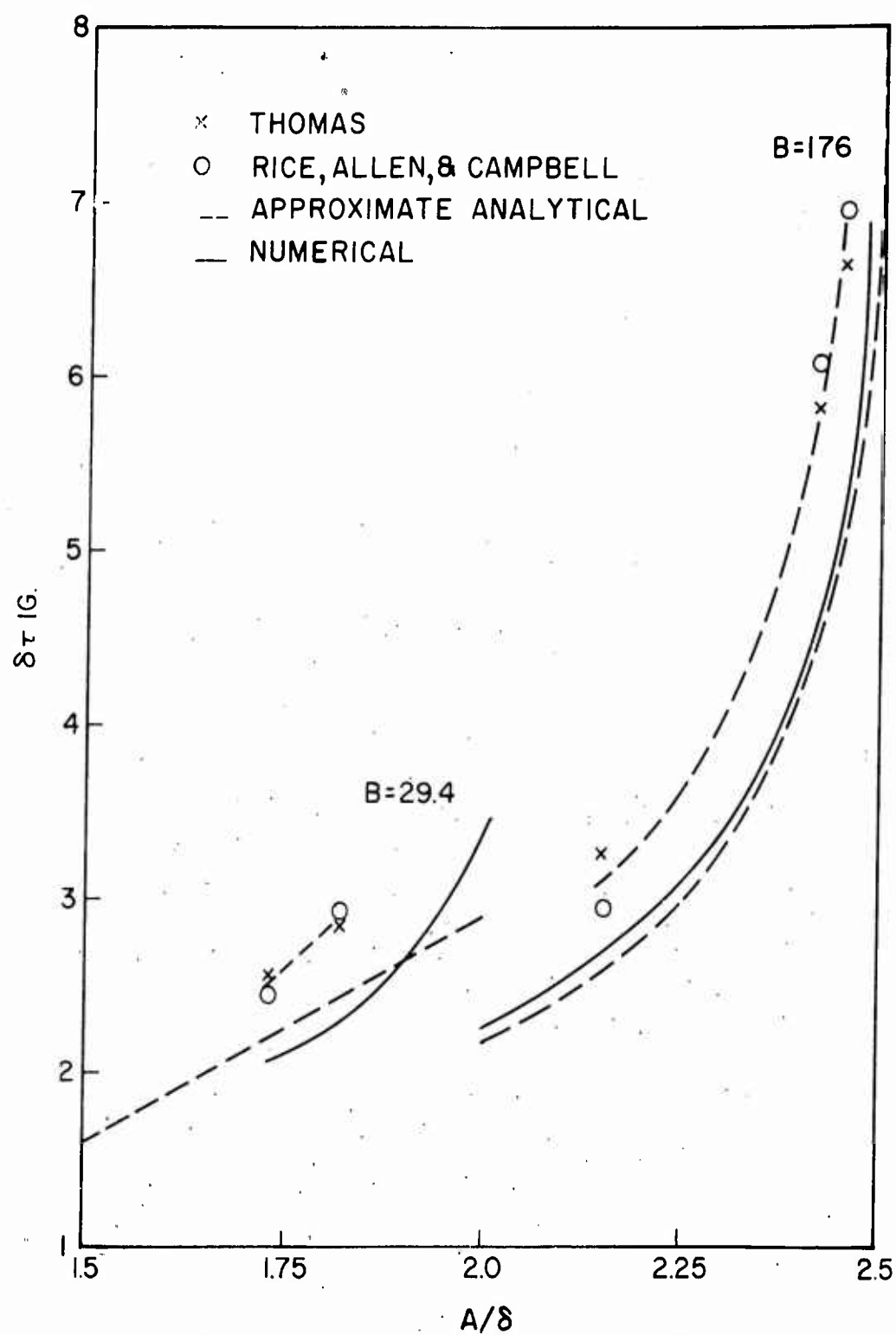
FIGURE 5. COMPARISON OF IGNITION DELAY RESULTS

solutions of a linearization of (1a). The agreement was qualitatively
satisfactory, but the ignition delay was underestimated somewhat. It
was suggested that this was due to the neglect of reactant consumption.
In Fig. 6a and 6b, the experimental results are shown along with Kinbara
and Akita's calculated curves and numerical solutions for $B = 10$ and two
lower values of B. It can be seen that a value of B of about 5 leads to a
marked improvement in the agreement between theory and experiments.
Unfortunately, Kinbara and Akita do not give the value of Q (the heat of
decomposition of their sawdust), but $B = 5$ does correspond to a reasonable
value.
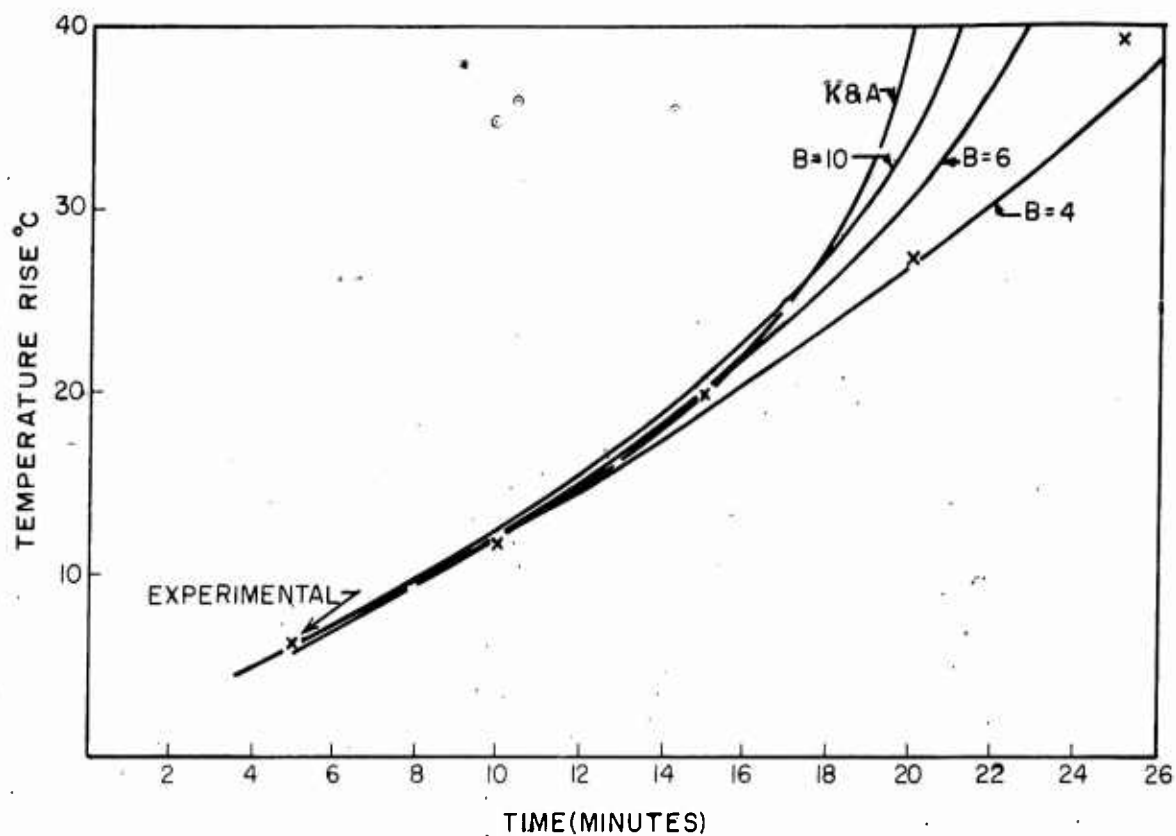
6a – 3.7cm SPHERE AT 196°C; A/δ = .46
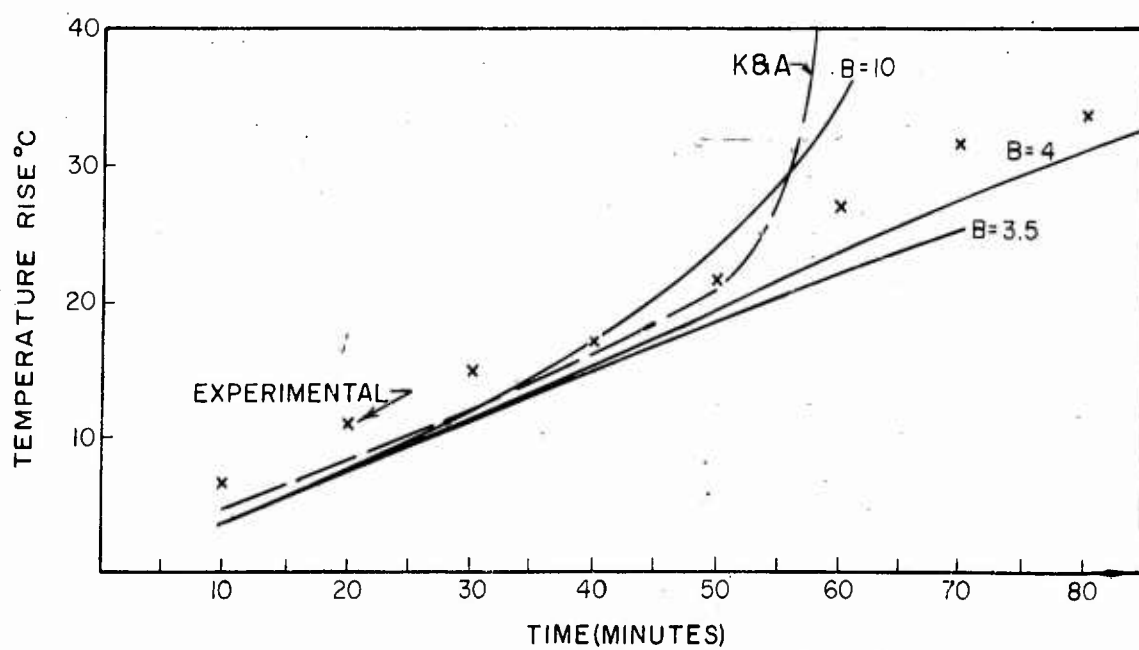
6b – 5.25 cm SPHERE AT 179°C; A/δ = 0.65

FIGURE 6. COMPARISON OF EXPERIMENTAL AND
THEORETICAL TEMPERATURE HISTORIES

DISCUSSION

The mathematical analysis of the differential equations of non-steady explosion theory has been greatly simplified by using the temperature instead of the time as the independent variable. In particular, for a first order reaction, the numerical solution is greatly simplified because a nonlinear relation reduces to a quadratic which can be solved explicitly.

In the approximate analytical treatment of the equations, two approximations are involved. It is believed that the principal source of error is the use of the linear relation, (8), between composition and temperature as a first approximation to the solution rather than the use of the rational fraction, (11), to approximate the exponential. In particular, it could be anticipated that the linear approximation between composition and temperature would not be accurate near a temperature maximum. This probably explains the error in the determination of the critical conditions where a temperature maximum is involved and the relative accuracy of the determination of ignition delay for supercritical conditions where no maximum is involved

It is, of course, true that, since there is an adjustable parameter, q, involved in the calculation, the determination of the critical condition could probably be improved by some other method of evaluating q. The method used in this paper of matching at a fixed value of $P\theta$ gave a value

of q which was essentially independent of B. An examination of Thomas' expression indicated that, to improve our result, q should increase as $B^{1/3}$, so that no basic improvement can be expected from changing the value of $P\theta$. While other methods of evaluating q are possible (such as matching at a fixed value of θ rather than $P\theta$), it hardly seems worthwhile to attempt to patch up the analysis in this way, particularly since the exact numerical solution is so convenient.

The comparison between Akita's experiments and the calculations indicate that the agreement is improved by taking reactant consumption into account, but, as Akita did not specify the value of Q for the sawdust, a question remains as to whether the value of B which gives satisfactory agreement is the actual value for the material though it appears reasonable. In view of the uncertainty in the measurements and in the value of the other properties involved, the agreement appears as good as can be expected. It would, however, be of some interest to treat the problem by numerical solution of the full partial differential equations (1a) and (1b) in order to estimate the effect of the approximations involved in nonsteady explosion theory. A numerical procedure for solving the partial differential equation has been developed[8] but only a few preliminary calculations have been made as yet.

The numerical solutions for small values of $B(\leqslant 10)$ show that the transition between the super- and subcritical cases becomes less

distinct as B becomes small. Examination of (14) shows that the maximum temperature in the subcritical case increases as B decreases, while the maximum temperature in supercritical cases must be less than B, so that the distinction obviously becomes less sharp for small values of B In this region, it is necessary to use the numerical procedure rather than the analytical approximations which are essentially expansions in B^{-1}.

ACKNOWLEDGEMENT

REFERENCES

1. Gray, P and Harper, M J, "Thermal Explosions, Part I. Induction Periods and Temperature Changes Before Spontaneous Ignition," Transactions of the Faraday Society, 55, 4, pp 581-590, April 1959.

2. Thomas, P. H., "Some Approximations in the Theory of Self-Heating and Thermal Explosion," Transactions of the Faraday Society, 56, 6, pp 833-839, June 1960.

3. Thomas, P H., "The Effect of Reactant Consumption on the Induction Period and Critical Condition for a Thermal Explosion," Proceeding Royal Society, 262 A, pp 192-206, 1961

4. Levy, H, and Baggott, E. A, Numerical Solution of Differential Equations, Chapter 3, Dover, New York, 1950.

5. Kinbara, T., and Akita, K, "An Approximate Solution of the Equation for Self-Ignition," Combustion and Flame, 4, 2, pp. 173-180, June 1960.

6. Frank-Kamenetskii, D. A, "The Mathematical Theory of Thermal Explosions, II Induction Period Near the Explosion Limit; Correction for the Concentration Change," Acta Physiochemica, URSS, 20, pp 729-736 (1943).

7. Rice, O K., Allen, A O, and Campbell, H. C., "Induction Period in Gaseous Thermal Explosions," Journal American Chemical Society, 57, pp. 2212-2222, November 1935.

8. Squire, W., and Foster, C., "A Mathematical Study of the Mechanism of Wood Burning," Technical Progress Report No. 1, Contract CST-362, SwRI Project No 1-965-2, February 3, 1961

INITIAL DISTRIBUTION LIST

Contract CST-362

Wright Air Development Division
(ATTN: WCLEMH)
Wright-Patterson Air Force Base
Ohio   (1)

Federal Fire Council
4316 General Services Building
Washington 25, D. C.   (2)

National Research Council
National Academy of Sciences
Committee on Fire Research
Washington 25, D. C.   (2)

U. S. Department of the Interior
Bureau of Mines
Branch of Explosives Research
Washington 25, D. C.   (2)

National Science Foundation
Director for Mathematical,
  Physical, & Engineering
  Sciences
Washington 25, D. C.   (1)

Office of Civil and Defense
  Mobilization
Battle Creek, Michigan   (6)

Prof. H. C. Hottel
Director, Fuels Research Lab.
Massachusetts Institute of Tech.
Cambridge 39, Massachusetts   (1)

Dr. William H. Avery
Research & Development Supervisor
Applied Physics Laboratory
The Johns Hopkins University
8621 Georgia Avenue
Silver Spring, Maryland   (1)

Mr. Horatio Bond
Chief Engineer
National Fire Protection Assoc.
60 Batterymarch Street
Boston 10, Massachusetts   (1)

Mr. A. A. Brown, Director
Division of Forest Fire Research
U. S. Forest Service
Department of Agriculture
Washington 25, D. C.   (6)

Dr. Howard W. Emmons
Professor of Mechanical Eng.
Harvard University
Cambridge 38, Massachusetts   (1)

Mr. Joseph Grumer
Chief, Flame Research Section
U. S. Bureau of Mines
4800 Forbes Avenue
Pittsburgh 13, Pennsylvania   (1)

Mr. J. B. Macauley
Deputy Director
Defense Research & Engineering
Department of Defense
Washington 25, D. C.   (1)

Dr. Walter T. Olson, Chief
Propulsion Chemistry Division
Lewis Research Center
National Aeronautics & Space
  Administration
21000 Brookpark Road
Cleveland, Ohio   (1)

Dr. A. F. Robertson, Chief
Fire Research Section
National Bureau of Standards
Washington 25, D. C.   (100)

Dr. Walter G. Berl
Applied Physics Laboratory
8621 Georgia Avenue
Silver Spring, Maryland   (1)

Mr. B. P. Botteri (WWRMFE-3)
Wright Air Development Division
Wright-Patterson Air Force Base
Ohio   (1)

Dr. Mathew M. Braidech
Director of Research
National Board of Fire Underwriters
85 John Street
New York 38, New York   (1)

Mr. Clarence F. Castle
Chief, Services Division
Properties and Installation
Office Assistant Secretary of Defense
Washington, D. C.   (1)

Dr. Bernard Lewis, President
Combustion and Explosives Research, Inc.
1007 Oliver Building
Pittsburgh 22, Pennsylvania   (1)

Mr. Norman J. Thompson
Millers Hill Road
Dover, Massachusetts   (1)

Mr. Richard Tuve, Head
Engineering Research Branch
Chemistry Division
U. S. Naval Research Laboratory
Washington. D. C. (1)

Mr. G. B. Wareham, Chief
Equipment and Supplies Division
Office of Director of Defense
Research and Engineering
Washington 25, D. C. (1)

Commanding Officer
Office of Naval Research Branch Office
The John Crerar Library Building
86 East Randolph Street
Chicago 1, Illinois (1)

Commanding Officer
Office of Naval Research Branch Office
346 Broadway
New York 13, New York (1)

Commanding Officer
Office of Naval Research Branch Office
1030 E. Green Street
Pasadena 1, California (1)

Commanding Officer
Office of Naval Research Branch Office
Navy #100
Fleet Post Office
New York, New York (7)

Director, Naval Research Laboratory
Washington 25, D. C.
Attn: Technical Information Officer (6)
Chemistry Division (2)

Chief of Naval Research
Department of the Navy
Washington 25, D. C.
Attn: Code 425 (2)

Technical Library OASD (R & E)
Pentagon Room 3E1065
Washington 25, D. C. (1)

Technical Director
Research & Engineering Division
Office of the Quartermaster General
Department of the Army
Washington 25, D. C. (1)

Research Director
Chemical & Plastics Division
Quartermaster Research & Engineering
Command
Natick, Massachusetts (1)

Air Force
Office of Scientific Research (SRLT)
Washington 25, D. C. (1)

Commanding Officer
Diamond Ordnance Fuze Laboratories
Washington 25, D. C.
Attn: Technical Reference Section
(ORDTL 06. 33) (1)

Office of Chief of Staff (R & D)
Department of the Army
Pentagon 3B516
Washington 25, D. C.
Attn: Chemical Adviser (1)

Chief, Bureau of Ships
Department of the Navy
Washington 25, D. C.
Attn: Code 340 (2)

Chief, Bureau of Naval Operations
U. S. Department of the Navy
Washington 25, D. C.
Attn: Technical Library (3)
Code RRMA-2 (1)

ASTIA
Document Service Center
Arlington Hall Station
Arlington 12, Virginia (10)

Director of Research
Signal Corps Engineering Laboratories
Fort Monmouth, New Jersey (1)

Naval Radiological Defense Laboratory
San Francisco 24, California
Attn: Technical Library (1)

Naval Ordnance Test Station
China Lake, California
Attn: Head, Chemistry Division (1)

Commanding Officer
Office of Ordnance Research
Box CM, Duke Station
Durham, North Carolina (1)

Brookhaven National Laboratory
Chemistry Division
Upton, New York (1)

Atomic Energy Commission
Research Division, Chemistry Branch
Washington 25, D. C. (1)

Atomic Energy Commission
Library Branch
Technical Information ORE
Post Office Box E
Oak Ridge, Tennessee   (1)

U. S. Army Chemical Warfare Laboratories
Technical Library
Army Chemical Center, Maryland   (1)

Office of Technical Services
Department of Commerce
Washington 25, D. C.   (1)